

Interactive comment on “Remote monitoring of seismic swarms and the August 2016 seismic crisis of Brava, Cape Verde, using array methods” by Carola Leva et al.

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Response to the interactive comment on “Remote monitoring of seismic swarms and the August 2016 seismic crisis of Brava, Cape Verde, using array methods” by Carola Leva et al.

Anonymous Referee #1

We would like to thank the reviewer for the helpful comments and constructive suggestions.

R1: The paper by Leva et al. (NHES 2020-225), at its stage, focus on an important

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issue, which is the recognizing the precursors of intruding magma at crustal levels, and also the fact the Brava might be a dormant volcano, thus a contribution for the volcanic risk reduction. Despite the good approach, I have nevertheless some comments and remarks, which are the following: In line 6 it is stated that a seismic crisis occurred on Brava during the first two days of August, and in line 10 that the experiment started about only 10 month before. Which seismic baseline do you have before October 2015? Was the crisis already occurring in or before October 2015? Was the first two days just a culmination of the crisis?

A.: This is a very good point and we will include it in the discussion. We do not have access to data before October 2015, thus our baseline starts in October 2015 and we cannot comment on the seismicity before our study. However, Faria and Day (2017) state that the seismicity from 2011 to 2015 showed a constant rate with “sporadic peaks” and changed after an earthquake with magnitude M4 in September 2015. We will include this information in the discussion.

R1: The total number of earthquakes mentioned in line 11 is the total recorded by the array during the experiment, including those of Fogo and Brava, or just those of Brava?

A.: This is the total number of local earthquakes recorded by the network, including earthquakes of Fogo and Brava.

R1: In lines 15 and 34 you pretend to show that a remote array (35 km away from the epicenters) is suitable to monitor a volcanic seismic crisis. However, in lines 155 to 157 it is mentioned the results of others authors that recorded tremors and long-period events, which the array used in this experiment wasn't able to record because it was too far away. It seems that this is a contradiction, because one of the crucial signals to be recorded in order to monitor a volcano is both long-periods events and tremors episodes. If a network/array is unable to record those signals there is no advantage to use them.

A.: A local network, of course, can provide further (sometimes more) information. How-

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ever, without the remote array we would not have any information about the seismic crisis on Brava and that is an obvious advantage. We show how this data can be used to gain as much relevant information as possible.

R1: The depths of hypocentres reported by Faria and Fonseca (NHES, 2014) beneath Brava are mostly variable and there is no evidence that they are clustered at 5 km. Thus, instead of fixing the depths of all the earthquakes to 5 km (line 90), why was it not tried several depths in order to minimize the errors ellipses, which are already quite big as suggested by the figure 5 (b).

A.: We performed a careful analysis of the contributions to the error of the epicentral distance by evaluating the influence of all parameters used for the distance estimation. It turned out, that a variation of the event depth only has a minor impact on the result, compared to other variables (lines 91, 94-97). After this error analysis we found that an error of 10% for the distance in general covers best the errors resulting from the uncertainties of the distance estimation (lines 97/98). We decided to use this relative conservative estimate for the error to incorporate the uncertainties of the simple two-layer assumption, including the uncertainties of the depth. This is already described in the text, but we will clarify this point during revision.

R1: In lines 127 and 128 it is stated that “Most of the volcanic-tectonic earthquakes occurred beneath the southern part of Brava”. It is most appropriate to say “located” instead of occurred, because yours locations are not so precise.

A.: Thank you for pointing this out, we will modify this in the revised manuscript.

R1: What is the relevance for this paper to include the results of the paper about Fogo (lines 132-134)?

A.: We include the results here, because the earthquakes beneath Fogo are a rare observation and this information helps to provide a more complete image of seismicity in the region, which can be seen when comparing Figures 5, 6, 8 and 9.

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R1: Line 143 (pag. 5): please precise if the observation “. . . periods with elevated seismicity frequently occur beneath and around Brava.” refers to the period of the experiment. If so (which seems not to be the case because your data spans only two years, or otherwise include a reference), it is more suitable to state “. . . periods with elevated seismicity frequently occurred beneath and around Brava during the experiment.”

A.: Thank you for the suggestion, we will modify this statement in the revised manuscript.

R1: The first phrase in line 149 (pag. 5) refers to a period during the time span by your experiment or is a general characteristic of Brava seismicity? If it is the former, please precise, otherwise include a reference.

A.: Thank you for pointing this out. Both is the case, the seismicity is characterized by this shift, which we observe. Comparing the earthquake locations from former studies, this feature is confirmed. We will precise this statement and include the references.

R1: It is not clear in the first reading about the exact timing of the evolution of the seismic activity recorded on Brava during the experiment (e.g. lines 180 to 185 pag. 6). I recommend ordering it in time (and just mention it afterwards if necessary).

A.: We will change the order of the description in the revised manuscript.

R1: In line 181 (pag. 6) it is stated: “. . . movement of the earthquake locations is related to magmatic processes.”, please justify or include a reference.

A.: As suggested, we will include a reference in the manuscript.

R1: Distinction between offshore or around Brava (which appears in several parts of the text) and underneath Brava must be clearer, since a volcanic island must be seen as a whole including the submarine part of its edifice. I suggest to include in the maps a profile of the topography/bathymetry as it may help to make clearer whether the earthquakes were really offshore or (when located in the sea) on the submarine roots

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of the island.

A.: As suggested, we will add additional contour lines to the maps shown.

R1: It is stated all along the text the terms migration, movement, shift of the seismicity. I have two observations concerning the use of those terms: 1- the uncertainties of the locations are too big (fig 5b), thus it may be that the cause of the migration/shift/movement it is just due to the random errors of the locations. 2-Examining figures 4 (a-b) and 5 (a) it seems that seismic activity was present at several places at the same time, although more intense in one zone than others. So, instead of using those terms, isn't it more suitable to say that likely (due to big errors ellipses) the seismic activity became more intense (in terms of rate) in a certain zone than others?

A.: While our observations cannot constrain individual earthquake locations exactly, we can still detect systematic shifts in seismic activity, even if random errors are taken into account (as we have done). From our observations, we cannot confirm (nor fully exclude) that there is a continuous wide-spread low-level activity in the entire region. We therefore prefer to describe our observations by "shift" rather than by "variations of intensity". But we agree that "migration" or "movement" may be less appropriate, as this may give the impression that events are directly related (as if aligned along a common fault, which is probably not the case here). We will modify the expressions in the revised version.

R1: Final remarks: the geological setting and geotectonic of Brava were not taken in account during the discussion and/or conclusions. Why was the possibility of the movement of the faults (Madeira et al., 2010) ruled out?

A.: We cannot completely rule out this possibility. However, for a comment on the link between the earthquakes and the faults, we would need a precise location in addition to focal mechanisms of the earthquake. Being unable to determine the depth makes this even more difficult. However, we can suggest a possible magmatic origin, as the earthquakes occur in swarms and not in a mainshock-aftershock sequence, which

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would be expected for tectonic events.

R1: Or why a process of uplift episode of the island (Ramalho, 2010) was not discussed?

A.: Ramalho state that Brava has experienced significant uplift, which cannot be explained by a regional uplift across the swell, but rather by a local uplift. The cause of the uplift could e.g. be the magmatic intrusion below the edifice. A failed eruption could contribute to such an uplift, however we cannot comment on the amount of material added and thus on a potential uplift. Taken together our observations of 2016 and the observation of Faria and Day (2017), the seismicity in 2016 could indeed be part of an uplift episode. We will include the reference and extend the discussion accordingly.

R1: How often the CO₂ fluxes measurements were done? Were they sporadic or continually? Please specify when exactly in 2016 the anomalous CO₂ emission was observed?

A.: The CO₂ emission surveys were carried out every 2 years since 2010 (see references). There were two measurements taken in 2016, one in August and one in October/ November. The measurement of October/ November shows the highest values measured since 2010. The reason for the background level values of August is most likely the timing of the survey. In August the rainy season distorts the CO₂ emission measurements. Therefore, the surveys in the years before 2016 were taken outside of the rainy season, making it difficult to compare the August 2016 data to the data of previous years. The data of October/ November 2016 however are comparable to previous measurements and thus more meaningful (Pérez 2020, personal communication). The survey of 2018 showed lower levels of CO₂ emissions again. However, for details we have to refer the reader to the cited references.

R1: Anyway I recommend a better fundamentation volcanic nature of the seismic crisis hypothesis. Why the potential Brava volcanic hazards were not included (lines 198 to 201) or mentioned in the introduction. This would reinforce the importance of the

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volcanic monitoring on Brava and better fit the NHESS spirit.

A.: Thank you for pointing this out, we will adjust the discussion accordingly.

R1: I recommend adding a color scale to figure 1, and to make bathymetry clearer (it is hard from this figure to have an idea how the bathymetry is in vicinity of Brava is).

A.: We will add contour lines to the map, as also recommended for the other maps.

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